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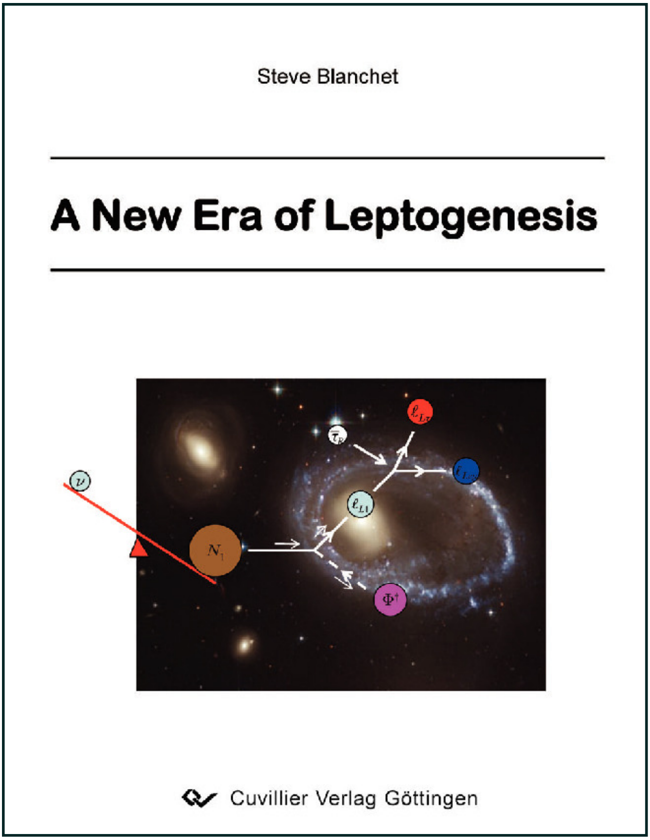
A new era of Leptogenesis



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Chapter 1

Introduction

1.1 The matter-antimatter puzzle

One can surely say that our understanding of the Universe has made a huge leap forward in the last few years. This is partly because the amount of data has dramatically increased, so that an epoch of "precision cosmology" has started. But this is also due to an accumulation of evidence for concepts that were still considered exotic not so long ago, such as dark matter and dark energy. Even though their nature is still unknown, at least there seems to be a consensus about their existence.

Nowadays, one speaks about a "Standard Cosmological Model", in analogy with its very successful counterpart of particle physics. The Standard Cosmological Model tells us that the Universe is in a phase of accelerated expansion and that the total energy in the Universe is shared among at least four components (see Fig. 1.1) which sum to $\Omega_{\text{tot}} \simeq 1$, meaning that the Universe is flat to a good precision. The dominant component (about 73%) is called dark energy, dark matter makes about 23%, ordinary matter (both luminous and dark) only 4% and neutrinos 0.2–2%, the uncertainty here stemming from the unknown absolute neutrino mass scale, as we shall see in Section 1.2.3.

It is well known that the nature of dark matter is still mysterious. The particle interpretation seems to be widely supported, and the candidates are numerous: axion, lightest supersymmetric particle (neutralino, gravitino), sterile neutrino, and many others.

Dark energy is probably a much bigger issue still than dark matter. It is supposed to drive the accelerated expansion, but its nature is very unclear. It also raises a fundamental question about how to treat the vacuum energy in quantum field theory.

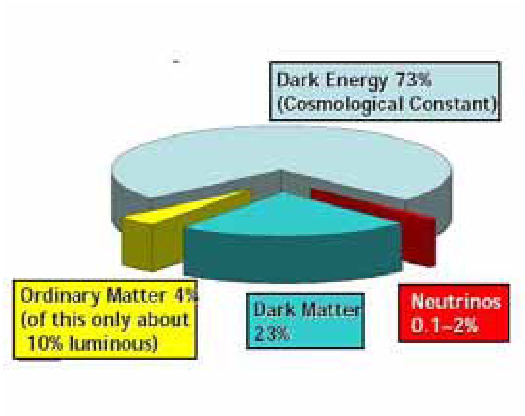

Figure 1.1: The mass-energy budget of the Universe.

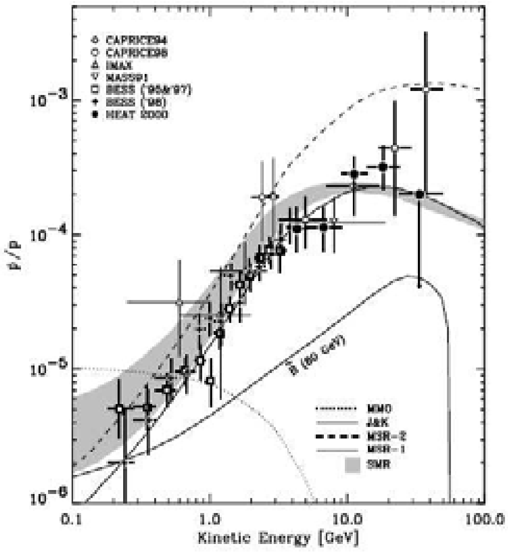

Figure 1.2: The antiproton-to-proton ratio at the top of the atmosphere, as observed (points) and predicted from the models (lines) [1].

Ordinary matter, which constitutes our bodies as well as the Earth and the stars, does not seem at first to introduce any challenge to our understanding. However, this naive perception is wrong because two very puzzling questions remain:

1) Why is antimatter essentially absent in the observable Universe?

2) Why is the number density of baryons so small compared to photons or neutrinos?

These two questions are puzzling because, according to the Standard Big-Bang Theory, matter and antimatter evolved in the same way in the early Universe. On the other hand, today the observable Universe is composed almost exclusively of matter. Antimatter is only seen in particle physics accelerators and in cosmic rays. Moreover, the rates observed in cosmic rays are consistent with the secondary emission of antiprotons, $n_{\bar{p}}/n_p \sim 10^{-4}$ (see Fig. 1.2).

Ordinary matter is composed of baryons (protons, neutrons) and leptons (electrons). One can assign an experimentally conserved number to baryons and leptons. Baryons and leptons carry one unit of these numbers, whereas antibaryons and antileptons carry one negative unit. In this way one can say that the predominance of matter over antimatter is equivalent to the existence of a net baryon number.

Following the Standard Big-Bang Theory and relying on the Standard Model (SM) of particle physics, the relic density of baryons, i.e. nucleons here, can be easily estimated. One has the usual Boltzmann equation for the number density of baryons n_B (or antibaryons)

$$\frac{\mathrm{d}n_B}{\mathrm{d}z} + 3Hn_B = -\langle\sigma_A|v|\rangle \left[n_B^2 - (n_B^{\mathrm{eq}})^2\right], \tag{1.1}$$

where $z = M_B/T$, M_B is the baryon mass, H the Hubble expansion rate, n_B^{eq} the equilibrium number density of baryons, and T the cosmic temperature. The collision term on the right-hand side is given in terms of an thermally-averaged annihilation cross-section $\langle\sigma_A|v|\rangle$, whose definition can be found in [2] for example. Eq. (1.1) can be conveniently rewritten in terms of the variable n_B/n_γ, where n_γ is the number density of photons, allowing one to factor out the effects of the expansion of the Universe. One obtains

$$\frac{\mathrm{d}(n_B/n_\gamma)}{\mathrm{d}z} = -\frac{n_\gamma z}{H(M_B)}\langle\sigma_A|v|\rangle \left[\left(\frac{n_B}{n_\gamma}\right)^2 - \left(\frac{n_B^{\mathrm{eq}}}{n_\gamma}\right)^2\right]. \tag{1.2}$$

In our case, the important annihilation channel is into pions (e.g. $p + \bar{p} \to \pi^+ + \pi^-$). Taking the averaged cross-section to be $\langle\sigma|v|\rangle = C_1 M_\pi^{-2}$, with $M_\pi \simeq 135$ MeV and where C_1 is a numerical factor of order unity, the freeze-out occurs at $T \sim 22$ MeV. Neglecting the entropy production in e^+e^--annihilations, one finds for today's abundance (subscript '0') [2]

$$\left.\frac{n_B}{n_\gamma}\right|_0 = \left.\frac{n_{\bar{B}}}{n_\gamma}\right|_0 \simeq 7 \times 10^{-20} C_1^{-1}. \tag{1.3}$$

Note that the ratio of baryon number density to photon number density today is usually referred to as the *baryon-to-photon ratio*,

$$\eta_B \equiv \left.\frac{n_B}{n_\gamma}\right|_0 . \tag{1.4}$$

The result of our simple computation, Eq. (1.3), is clearly a small number, which would perhaps explain the question 2) above. But one notices immediately a first problem, namely because the abundances of baryons and antibaryons are predicted in this way to be the same. Baryons and antibaryons do not evolve in distinctive ways so that one expects today the same amount of each of them. So, the argument we have just described leaves open the question 1) above. But let us for the moment ignore this point and try to see if the abundance of baryons matches observation.

The photon density follows directly from the measurement of the Cosmic Microwave Background (CMB) temperature and from Bose-Einstein statistics: $n_\gamma \sim T^3$. Determining the baryon content of the Universe is more difficult. Direct measurements are not accurate, because only a small fraction of baryons formed stars and other luminous objects (see Fig. 1.1). However, we can rely on two different indirect probes.

The first probe is Big-Bang Nucleosynthesis (BBN). The abundances of light elements such as ^{4}He, D, ^{3}He and ^{7}Li predicted by the standard theory of BBN crucially depend on η_B. Comparing predictions with observations, as shown in Fig. 1.3, the following baryon-to-photon ratio is inferred [3]:

$$\eta_B \simeq (5.5 \pm 1.0) \times 10^{-10}. \tag{1.5}$$

The CMB temperature anisotropies, very well measured by the WMAP satellite, offer the second probe. These anisotropies reflect the acoustic oscillations of the baryon-photon fluid which happened around photon decoupling. A precise computation can be done evolving Boltzmann equations for anisotropies, assuming that they are generated by quantum fluctuations during inflation. Fig. 1.4 illustrates how the amount of anisotropies with angular scale $\sim 1/\ell$ depends on η_B. The baryon-to-photon ratio obtained from 3 years of WMAP data is [4]

$$\eta_B \simeq (6.1 \pm 0.2) \times 10^{-10}. \tag{1.6}$$

The synthesis of light elements occurred during the first 3 minutes in the history of the Universe, whereas the photon decoupling occurred when the Universe was 400 thousand years old. The fact that these two completely different probes of the baryon content of the Universe give compatible results is one of the great successes of modern cosmology.[1]

It should now be clear that the result from the "classical" computation of the baryon density given in Eq. (1.3) is at odds with the observed value, Eq. (1.6). In order to avoid the "baryon annihilation catastrophe" leading to the value in Eq. (1.3), one has to generate a primordial asymmetry between baryons and antibaryons. This small asymmetry, *at the level of one part in one billion*, would imply that after the annihilation process has occurred at full strength, one remains with the small excess of baryons over antibaryons. The problem of generating this small excess of baryons over antibaryons is often called the *baryogenesis problem*.

[1]Throughout the thesis, we shall exlusively use the value of η_B obtained from CMB temperature anisotropies, Eq. (1.6), which has much smaller errors.

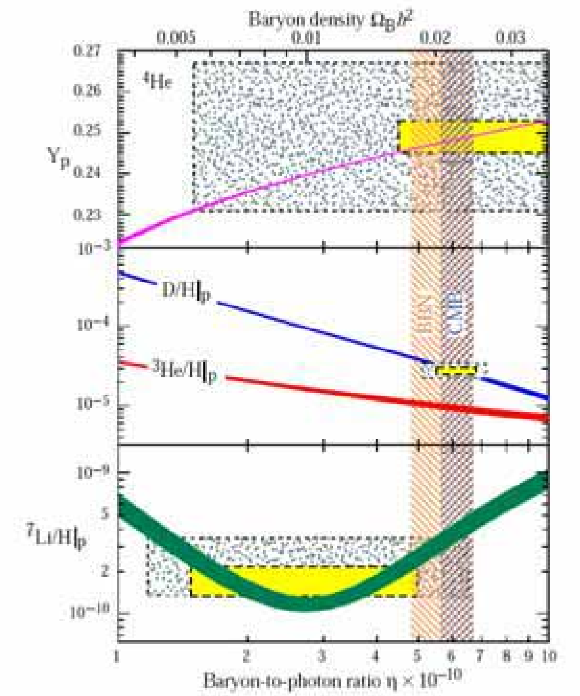

Figure 1.3: The observed abundances of light elements compared to the standard BBN predictions [5]. The smaller boxes indicate 2σ statistical errors, the larger ones $\pm 2\sigma$ statistical and systematic errors.

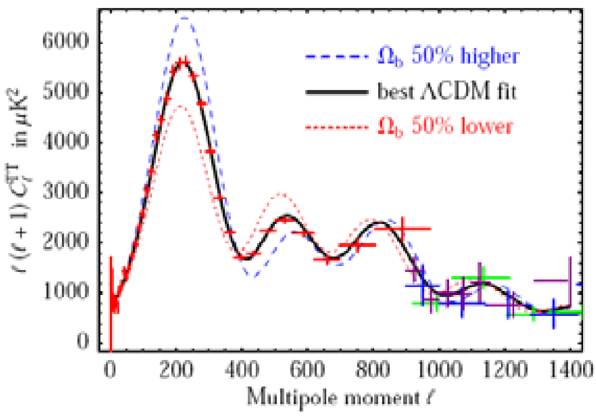

Figure 1.4: The dependence of CMB temperature anisotropies on the baryon abundance Ω_b (or η_B), compared with data [6].

The solution to the baryogenesis problem requires the generation of a small baryon asymmetry primordially. Sakharov, in 1967, enunciated the three necessary conditions for such a process to be possible at some stage in the history of the Universe [7]:

1. Baryon number violation.

2. C and CP violation.

3. Departure from thermal equilibrium.

In principle, the SM contains all these ingredients. Indeed,

1. Due to the chiral nature of weak interactions, B and L are not conserved [8]. At zero temperature, this has no observable effect due to the smallness of the weak coupling. However, as the temperature reaches the critical temperature $T_{\rm EW}$ of the electroweak phase transition, B and L violating processes come into thermal equilibrium [9, 10]. The rate of these processes is related to the free energy of the sphaleron-type field configurations which carry topological charge [11]. In the SM they lead to an effective interaction operator of all left-handed fermions, $O_{B+L} = \prod_i Q_{Li}Q_{Li}Q_{Li}\ell_{Li}$, which violates baryon and lepton number by three units. On the other hand, $B-L$ remains conserved.

2. The weak interactions of the SM violate C maximally and violate CP via the Kobayashi-Maskawa mechanism [12]. The latter originates from the quark mixing matrix, often called the Cabibbo-Kobayashi-Maskawa (CKM) matrix, which contains one CP-violating phase. This phase is known to be non-zero since CP violation has been observed in the K and B mesons systems (see e.g. the review on CP violation in [5]).

3. A strongly first-order electroweak phase transition in the early Universe could provide the out-of-equilibrium condition. A first-order phase transition proceeds via nucleation and growth of bubbles [13].

This scenario is called *electroweak baryogenesis in the Standard Model*. However, it fails for two reasons. First, it turns out that, for the electroweak phase transition to be strongly first order, the mass of the Higgs particle should be smaller than about 45 GeV [14] (see also [15]). However, LEP II gives the well-known bound $M_h > 114$ GeV [5]. Second, the source of CP violation in the quark sector is far too small, due to the smallness of some of the quark masses [16].

In conclusion, successful baryogenesis requires physics beyond the SM, just as the dark matter and dark energy problems! One intriguing solution to the problem of baryogenesis is deeply connected with the neutrino sector and in particular with neutrino masses. This is the topic of the next section.

1.2 The puzzle of neutrino masses

1.2.1 Theory of neutrino oscillations

Even with tiny masses, massive neutrinos can behave very differently from massless ones. In particular, massive neutrinos naturally lead to neutrino mixing and to neutrino oscillations, which have been recently observed, as we shall see below. Let us sketch how this happens.

Consider a neutrino beam created in a charged current interaction along with the antilepton α^+, $\alpha = e, \mu, \tau$. By definition the neutrino created is called ν_α. In general, this is not a physical particle, but rather a superposition of physical fields ν_i with different masses m_i:

$$|\nu_\alpha\rangle = \sum_i U^\star_{\alpha i}\,|\nu_i\rangle, \tag{1.7}$$

where U is the lepton mixing matrix, also known as the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix [17–19]. By analogy with the CKM matrix in the quark sector, the lepton mixing matrix can be conveniently parametrized as

$$U = V \times \mathrm{diag}\,(\mathrm{e}^{\mathrm{i}\frac{\Phi_1}{2}}, \mathrm{e}^{\mathrm{i}\frac{\Phi_2}{2}}, 1), \tag{1.8}$$

$$V = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}\,\mathrm{e}^{-\mathrm{i}\,\delta} \\ 0 & 1 & 0 \\ -s_{13}\,\mathrm{e}^{\mathrm{i}\,\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix},$$

where $s_{ij} \equiv \sin\theta_{ij}$, $c_{ij} \equiv \cos\theta_{ij}$, δ and $\Phi_{1,2}$ are the Dirac and Majorana *CP*-violating phases, respectively. The Majorana phases, which are not present in the quark sector, are related to the possible Majorana nature of neutrinos (see Section 1.3).

For a simple-minded approach to the propagation of the state $|\nu_\alpha\rangle$, we assume that the 3-momentum $\mathbf{p}$ of the different components in the beam are the same. However, since their masses are different, the energies of all these components cannot be equal. Rather, for the component ν_i, the energy is given by the relativistic energy-momentum relation $E_i = \sqrt{\mathbf{p}^2 + m_i^2}$. After a time t, the evolution of the initial beam, Eq. (1.7), assuming that neutrinos are stable particles, gives

$$|\nu_\alpha(t)\rangle = \sum_i e^{-\mathrm{i}E_i t} U^\star_{\alpha i} |\nu_i\rangle. \tag{1.9}$$

Since all E_i's are not equal if the masses are not, Eq. (1.9) represents a different superposition of the physical eigenstates ν_i compared to Eq. (1.7). In general, the state in Eq. (1.9) can therefore show properties of other flavor states. The amplitude of finding a $\nu_{\alpha'}$ in the original ν_α beam is

$$\langle \nu_{\alpha'}|\nu_\alpha(t)\rangle = \sum_i e^{-\mathrm{i}E_i t} U^\star_{\alpha i} U_{\alpha' i}, \tag{1.10}$$

using the fact that $\langle \nu_i|\nu_j\rangle = \delta_{ij}$. The probability of finding a $\nu_{\alpha'}$ in the original ν_α beam at any time t is then the modulus squared of the amplitude, $P_{\nu_\alpha\to\nu_{\alpha'}}(t) = |\langle \nu_{\alpha'}|\nu_\alpha(t)\rangle|^2$. In all practical situations, neutrinos are extremely relativistic, so that one can approximate the energy-momentum relation as $E_i \simeq |\mathbf{p}| + m_i^2/(2|\mathbf{p}|)$ and replace t by the distance x traveled by the beam. After a few manipulations one can finally write the vacuum oscillation probability as

$$\begin{aligned} P_{\nu_\alpha\to\nu_{\alpha'}}(x) &= \delta_{\alpha\alpha'} - 4\sum_{i>j} \mathrm{Re}\left(U^\star_{\alpha i} U_{\alpha' i} U_{\alpha j} U^\star_{\alpha' j}\right) \sin^2\left(\frac{\Delta m^2_{ij}}{4E}x\right) \\ &\quad +2\sum_{i>j} \mathrm{Im}\left(U^\star_{\alpha i} U_{\alpha' i} U_{\alpha j} U^\star_{\alpha' j}\right) \sin\left(\frac{\Delta m^2_{ij}}{4E}x\right), \end{aligned} \tag{1.11}$$

where $E \simeq |\mathbf{p}|$ and $\Delta m^2_{ij} \equiv m_i^2 - m_j^2$. From this formula it is apparent that neutrino oscillations require non-zero neutrino masses and mixings.

1.2.2 Experimental evidence for neutrino oscillations

The last 10 years have been extremely successful for the field of neutrino physics. In 1998, the Super-Kamiokande experiment in Japan reported the first compelling evidence for neutrino oscillations as a way to explain the anomaly in atmospheric neutrinos. Super-Kamiokande not only confirmed the previously found deficit in ν_μ-type events but also measured a zenith angle dependent ν_μ-deficit which was inconsistent with expectations based on calculations of the atmospheric neutrino flux. The neutrino oscillation explanation $\nu_\mu \to \nu_\tau$ with a quasi-maximal mixing angle [20] appeared therefore as the most convincing one.

Two dedicated laboratory experiments have been conceived in order to check this picture. The experiment K2K in Japan, which collected data until

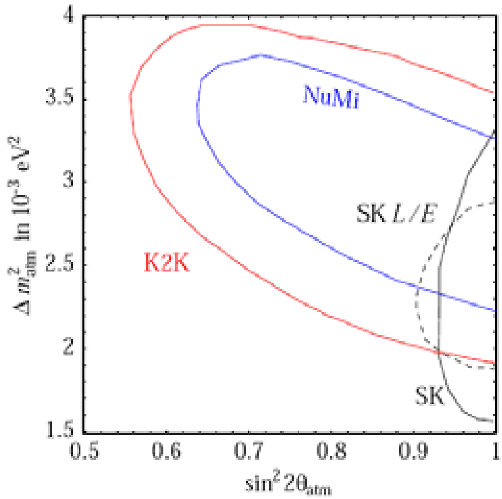

Figure 1.5: Best fit regions at 90% C.L. for atmospheric and accelerator neutrinos [23].

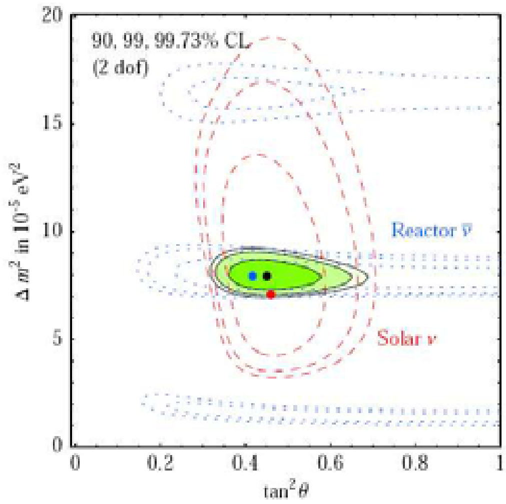

Figure 1.6: Best fit regions at 90, 99 and 99.73% C.L. for solar and reactor neutrinos [23].

November 2004, used a pulsed beam of muon-neutrinos produced at KEK and detected at Super-Kamiokande (distance of 250 km). The currently running MINOS experiment uses a pulsed beam of muon-neutrinos produced at NuMI (Fermilab), and the far detector is located at a distance of 735 km in the Soudan mine, Minnesota. Both experiments point to a neutrino oscillation interpretation of their data, with mixing parameters compatible with those explaining the atmospheric anomaly [21, 22]. A summarizing plot for "atmospheric" neutrinos can be found in Fig. 1.5. The best-fit parameters are [23]:

$$|\Delta m^2_{32}| \equiv \Delta m^2_{\rm atm} = (2.5 \pm 0.2) \times 10^{-3} {\rm eV}^2, \quad (1.12)$$
$$\sin^2 2\theta_{23} = 1.02 \pm 0.04, \quad (1.13)$$

where the ranges indicated are at 1σ.

Neutrinos from the Sun were first studied by Ray Davis in the Homestake mine in South Dakota in the 1960's [24]. This pioneering work made use of the radiochemical technique, $\nu_e + {}^{37}{\rm Cl} \to e^- + {}^{37}{\rm Ar}$. He quickly found that the observed flux was smaller than the one predicted by Bahcall and collaborators from the Standard Solar Model [25]. The *solar neutrino puzzle* was born. Later, other experiments were conceived to check this deficit in solar neutrinos: Kamiokande [26] and later Super-Kamiokande [27], which used the water Cherenkov technique, also found a deficit, as well as SAGE [28] and